Application No. 10/708,730
Amendment Dated November 6, 2006
Reply to Office Action of May 5, 2006

Amendments to the Specification:

Please replace the paragraphs [0006], [0013], [0016], [0029], [0034], [0037], [0038], [0040], [0042], [0045], [0046], [0049], [0054], [0058], [0060], [0061], and [0069] with the following rewritten paragraphs:

--[0006] *Aberration limitation:* In the case of the Rowland design, when Θ_{div}>4DEG, serous aberration in the refocusing beam will occur to limit wavelength resolution. This is shown in Fig. 1C illustrating the ray tracing for the typical Rolwand-Echelle design at 4, 8, and 16DEG diffraction. The ray tracing will allow us to see potential focusing distortion or aberration[[.]] at the exit slit. In the figure, we show the focusing behavior for two sets of rays with wavelengths separated by 0.4nm. From the figure, we see that their focused spots clearly separate when Θ_{div}=4DEG. However, when Θ_{div}=8DEG, the focused spots began to smear out. There is substantial distortion for the focusing rays when Θ_{div}>4DEG. Further simulations based on numerical solutions to Maxwell[[”]]’s wave equations using finite-difference time-domain (FDTD) method also show similar onset of focused spot size distortion at Θ_{div}>4DEG. In short, the current designs are close to their resolution-size (RS) limits and cannot be made substantially more compact without losing wavelength resolution.

[0013] $d(\sin\Theta_2 - \sin\Theta_1) = m\lambda_c/n(1)$

[0016] All other grooves, specified by its position vector X_l[[”]]’s, are located on the same circle of radius R defined by the initial three groove positions X, X, and X_{-1}. X_l[[”]]’s are also equally spaced along a chord that is parallel to the tangent of the grating center. In other words, the projection of the displacement vector $X_l - X_{i-1}$ on this chord always has the same length. Specifically, the position vectors of these grooves can be written as $x_i = (di, R - (R^2 - (di)^2)^{½})$, and $X_{-i} = (di, R - (R^2 - (di)^2)^{½})$[[.]].

[0029] We have improved on the current Rowland design, enabling curved-grating spectrometer with 10-100x smaller linear size (or 100-10,000x smaller area) using our HR-CCG with large-angle aberration-corrected design. The typical Rowland design can only reach a useful diffraction angle Θ_{diff} of ~4DEG, beyond which serous aberration in the refocusing beam will occur to limit wavelength resolution. In Figure 5A we show the angular resolution of the typical Rowland design at 16DEG diffraction angle compared with our HR-CCG design at 50DEG. We see that our "large-angle aberration-corrected grating" design has much better angular resolution: different direction rays are well converged to a point on the focal circle. This translates to much smaller RS factor or size. We have used discrete time solution of vectorial Maxwell[["]]'s equations to simulate the HR-CCG design, which verified the high resolution nature of our grating as predicted by the ray-tracing method.

[0034] $d(\sin ⊟\underline{\Theta}_2 - \sin ⊟\underline{\Theta}_1) = m ⊟\underline{\lambda}_c / n(1)$

[0037] Fifth, location of other grooves X_i[["]]'s are obtained by two conditions. The first of these conditions being that the path-difference between adjacent grooves should be an integral multiple of the wavelength in the medium. The first condition can be expressed mathematically by:

[0038] $[d_1(⊟\underline{\Theta}_1, S_1, X_1) + d_2(⊟\underline{\Theta}_2, S_2, X_i)] - [d_1(⊟\underline{\Theta}_1, S_1, X_{i-1}) + d_2(⊟\underline{\Theta}_2, S_2, X_{i-1})] = m⊟\underline{\lambda}/n,$ (2)

~~[0039] (2)~~

[0040] where $d_1(⊟\underline{\Theta}_1, S_1, X_i)$ is the distance from a i-th groove located at X_i to entrance slit 502 specified by Θ_1 and S_1, $d_2(⊟\underline{\Theta}_2, S_2, X_i)$ is the distance from i-th groove located X_i to detector 502 specified by Θ_2 and S_2, m is the diffraction order, and n is the refractive index of the medium. This mathematical expression is numerically exact for the optical path difference requirement in the diffraction grating and is actively adjusted for every groove on HR-CCG.

[0042] $f(\boxminus\underline{\Theta}_1, S_1, \boxminus\underline{\Theta}_2, X_i, X_{i-1}, \boxminus\underline{\lambda}_c, n, m) = const$ (3)

[0045] An exemplary embodiment of HR-CCG specified above is shown in FIG. 6. The radius of curvature at the grating center is R = 50 μm. Entrance slit 502 is located at an angle Θ_1 = 55°from the grating normal and distance S_1 = 28.68 μm from the grating center. Detector 506 is located at an angle Θ_2 = 27.2°the grating normal and distance S_2 = 37.65 μm from the grating center. The groove spacing at the grating center is chosen to be d = 3.6 μm so that diffraction order m = 10 is directed toward detector 506 located at Θ_2. As shown in FIG. 6, entrance slit 502 and detector 506 is not located on a circle tangent to the grating center. Three initial grooves are located at X_0 = (0, 0), X_1 = (3.6, 0.13), and X_{-1} = (-3.6, 0.13) which form a circle radius R = 50 μm. Other groove locations X_i[[”]]'s are obtained with the condition of each groove having a constant angular spacing from entrance slit 502 and optical path-difference condition (Eq. 2). In a mathematical form, this condition is expressed as,

$$\cos(\Delta\theta_i) = \frac{(X_i - X_{in}) \bullet (X_{i-1} - X_{in})}{|X_i - X_{in}||X_{i-1} - X_{in}|} = const \underline{\qquad (4)}$$

~~[0046] (4)~~

[0049] In this particular case, the position of entrance slit 502, exit slit 506 and the angular spacing between the grooves are X_{in}=(-23.49, 16.45), X_{det}=(-17.26, 33.46), and $\Delta\Theta_1$ = 4.13°. In this example, wave-font of the diverging input beam propagating toward the curved grating is sliced into a set of narrow beams with angular extension $\Delta\Theta$ by the curved-grating. Each beam with angular extension $\Delta\Theta$ undergoes reflective diffraction by each groove. At a particular wavelength, diffraction at a particular groove is equivalent to redirecting to a particular narrow beam into a detector 506 location with Θ_2. The position vectors X_i[[”]]'s calculated from Eq. (2) and Eq. (4) are listed in the Table 2. As shown in FIG. 6, the positions of grooves X_i are not on a circle tangent to grating.

[0058] Third, the relation between Θ_1, Θ_2, and the initial grove spacing d is given by the grating formula,$d(\sin\underline{\Theta}\boxminus_2 - \sin\ \underline{\Theta}\boxminus_1)=m\underline{\lambda}\boxminus_c/n$ where m is the diffraction order, n is the refractive index of the medium, and λ_c is the center of the operation wavelength.

[0060] Fifth, the location of other grooves X_i[[“]]'s are obtained by the following two conditions. The first condition being the path-difference between adjacent grooves should be an integral multiple of the wavelength in the medium, which s mathematically expressed as

[0061] $[d_1(\underline{\Theta}\boxminus_1,S_1,X_i)+d_2\ (\underline{\Theta}\boxminus_2,S_2,X_i)] - [\underline{\Theta}\boxminus_1,S_1,X_{i-1})+d_2\ (\underline{\Theta}\boxminus_2,S_2,X_{i-1})]=m\underline{\lambda}\boxminus/n,$ (2)

~~[0062] (2)~~

[0069] FIG. 7 shows a specific example of the HR-CCG with constant arc-length of the grooves and detector 506 at a tangent circle. The radius of curvature at the grating center is R = 100 μm. Entrance slit 502 is located at an angle Θ_1 = 45°from grating normal and a distance S_1 = 70.71 μm from the grating center. Detector 506 is located at an angle Θ_2 37.37°and distance S_2 = 79.47 μm from the grating center. Both entrance slit 502 and exit slit 506 are located on a tangent circle of radius 50 μm. The groove spacing at the grating center is chosen to be d = 4.2 μm so that diffraction order m = 12 is directed toward detector 506 located at an angle Θ_2 from the grating normal. Three initial grooves are located at X_0 = (0, 0), X_1 = (4.2, 0.008), and X_{-1} = (-4.2, 0.008) which form a circle of radius R = 100 μm. Other groove locations X_i[[”]]'s are obtained with the condition of arc-length of each groove ΔS_i is the same, i.e. ΔS_1. Equation (2) and (6) are simultaneously solved for a X_1 withX_{in} = (-50, 50), X_{det}= (-48.24, 63.15), and ΔS_1 = 4.201 μm for a given X_{i-1}. Groove locations, X_i[[“]]'s calculated in this method are listed in Table 3. As shown in FIG. 7, grooves in this grating are not located on a tangent circle.--

Please replace the abstract with the following rewritten abstract:

--~~21File name~~The present invention discloses a system comprising a compact curved grating (CCG) and its associated compact curved grating spectrometer (CCGS) module and a method for making the same. The system is capable of achieving very small (resolution vs. size) RS factor. In the invention, the location of entrance slit and detector can be adjusted in order to have the best performance for a particular design goal. The initial groove spacing is calculated using a prescribed formula dependent on operation wavelength. The location of the grooves is calculated based on two conditions[[.]]: ~~T~~the first one being that the path-difference between adjacent grooves should be an integral multiple of the wavelength in the medium[[.]] and ~~T~~the second one being specific for a particular design goal of a curved-grating spectrometer. In an embodiment, elliptical mirrors each with focal points at the slit and detector are used for each groove to obtain aberration-free curved mirrors. --